

Evolved Star Radii and Temperatures as Measured with Interferometry

Gerard van Belle, JPL

The PTI Collaboration, JPL

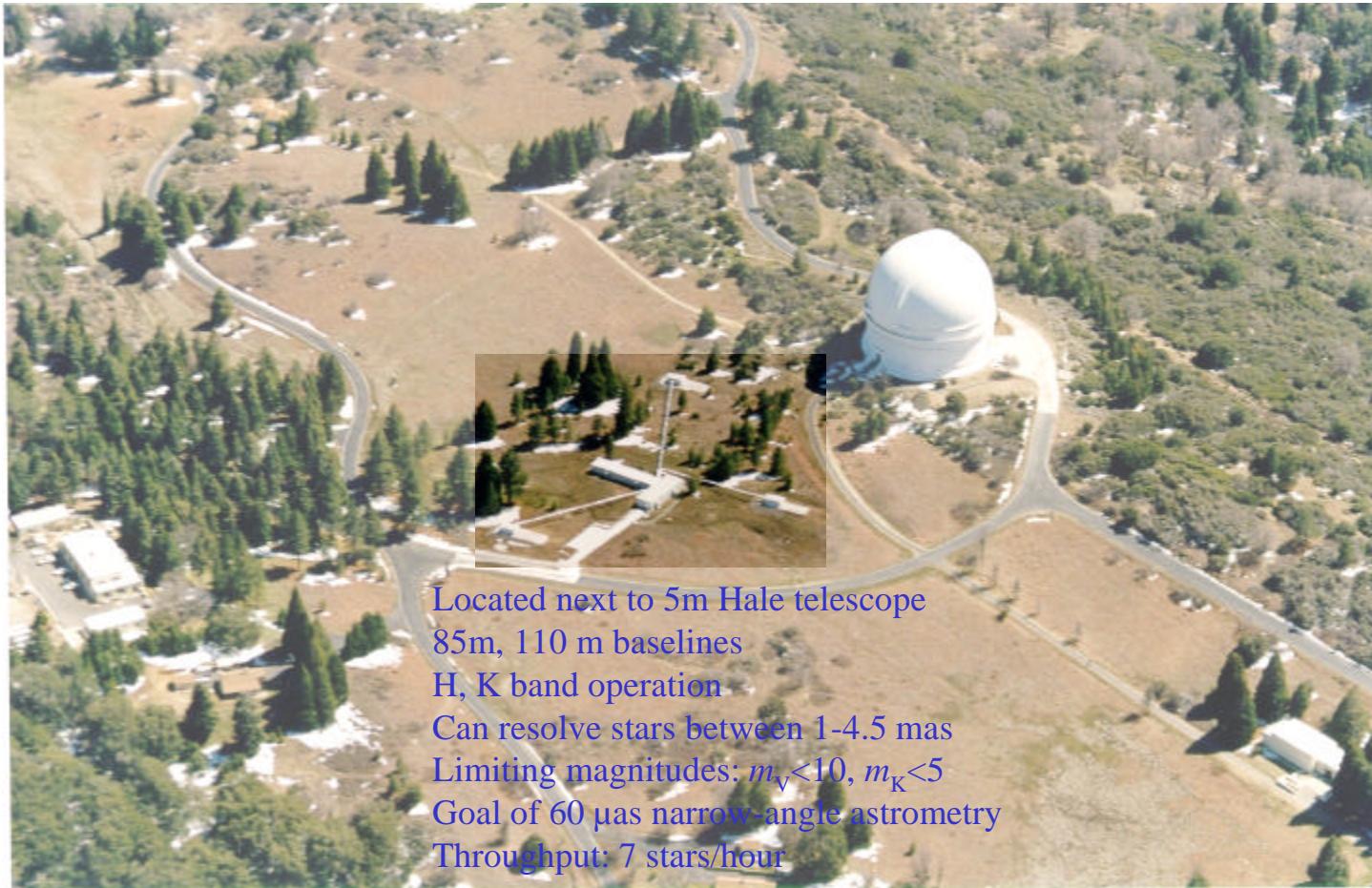
Robert Thompson, U. Wyoming

IAU Symposium 191: AGB Stars

Montpellier, France

Aug. 27 - Sept. 1, 1998

Palomar Testbed Interferometer



Located next to 5m Hale telescope
85m, 110 m baselines
H, K band operation
Can resolve stars between 1-4.5 mas
Limiting magnitudes: $m_V < 10$, $m_K < 5$
Goal of 60 μ as narrow-angle astrometry
Throughput: 7 stars/hour

Introduction

Abstract

- Hundreds of stellar angular diameters now available
 - Luminosity class I, II, III
 - Mira variables
 - Carbon, S-type stars
 - PTI producing ~100 a year
- Allows for direct measurement of linear radii with Hipparcos distances
- Allows for near-direct measurement of effective temperatures
 - Need to account for limb darkening
 - Small effect at K for most stars
- Can investigate relationships between these measurements and a variety of parameterizations

Recent advances in throughput, reliability and accuracy of results have greatly increased the scientific output of astronomical interferometers. Near-infrared results from the Palomar Testbed Interferometer (PTI) and the IR-Optical Telescope Array (IOTA) have been collected and are now presented as an unprecedented large database of stellar angular sizes for giants, supergiants, Mira variables and carbon stars. In conjunction with measurements of bolometric flux from available photometry, and the recent release of the Hipparcos results (Perryman 1997), temperatures as well as linear sizes are available for over 150 giant stars. Building upon the previous work found in Dyck *et al.* (1996, 1997, 1998) and van Belle *et al.* (1996, 1997, 1998), empirical dependencies of T and R upon spectral type and V-K, K-[12] colors are established from the data and presented. Unique capabilities of the PTI instrument utilized in this investigation of interest to the AGB community will also be discussed.

The Data

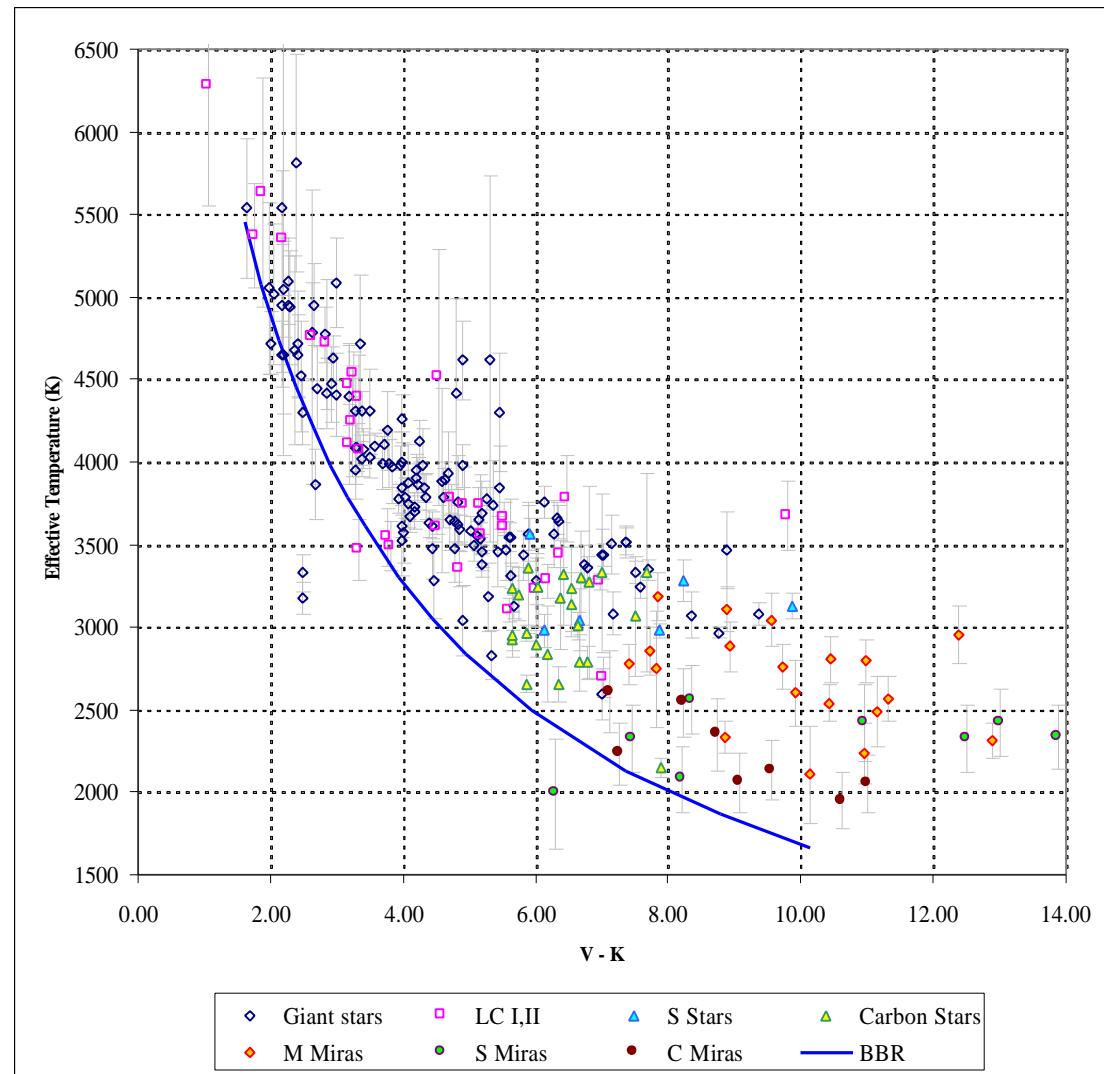
- Angular sizes from PTI, IOTA, lunar occultation data
 - 265 Luminosity class I, II, and III stars
 - 83 stars from PTI (van Belle *et al.* 1998), 82 stars from IOTA (Dyck *et al.* 1996, 1998), 36 stars from lunar occultations (Ridgway *et al.* 1980), 14 stars from intensity interferometry (Hanbury Brown 1974)
 - ~50 additional stars from pending PTI data
 - 53 Mira variables, S-type, carbon stars
 - 18 oxygen-rich Miras (van Belle *et al.* 1996), 5 carbon, 4 S-type Miras, 4 non-Mira S stars (van Belle *et al.* 1997) , 22 carbon stars (Dyck *et al.* 1997)
- Photometry from IRAS PSC (1986), Gezari *et al.* (1996), other sources
 - V-K and K-[12] colors
 - V band magnitudes for variables from AFOEV, AAVSO

Basic Parameters

- *Effective temperature* is defined as: $L = 4\pi s R^2 T_{\text{EFF}}^4$,
which can be rewritten as: $T_{\text{EFF}} = 1.316 \times 10^7 \left(\frac{F_{\text{TOT}}}{q_R^2} \right)^{1/4}$
 - F_{TOT} is the bolometric flux (W cm^{-2}), q_R is the Rosseland mean stellar angular diameter (mas)
- *Linear radius* is simply: $R = \frac{1}{2} q \times d$
 - Hipparcos (1997) distances now available
 - Uncertainties in parallax (typically $\sim 15\text{-}20\%$) still largest contribution to error
 - Range of sizes : $5\text{-}1000 R_{\text{SUN}}$
- *V,K=0 angular size* is given as: $q_{m_1=0} = q_{m_1} \times 10^{m_1/5}$
 - Scales sizes to a constant brightness distance

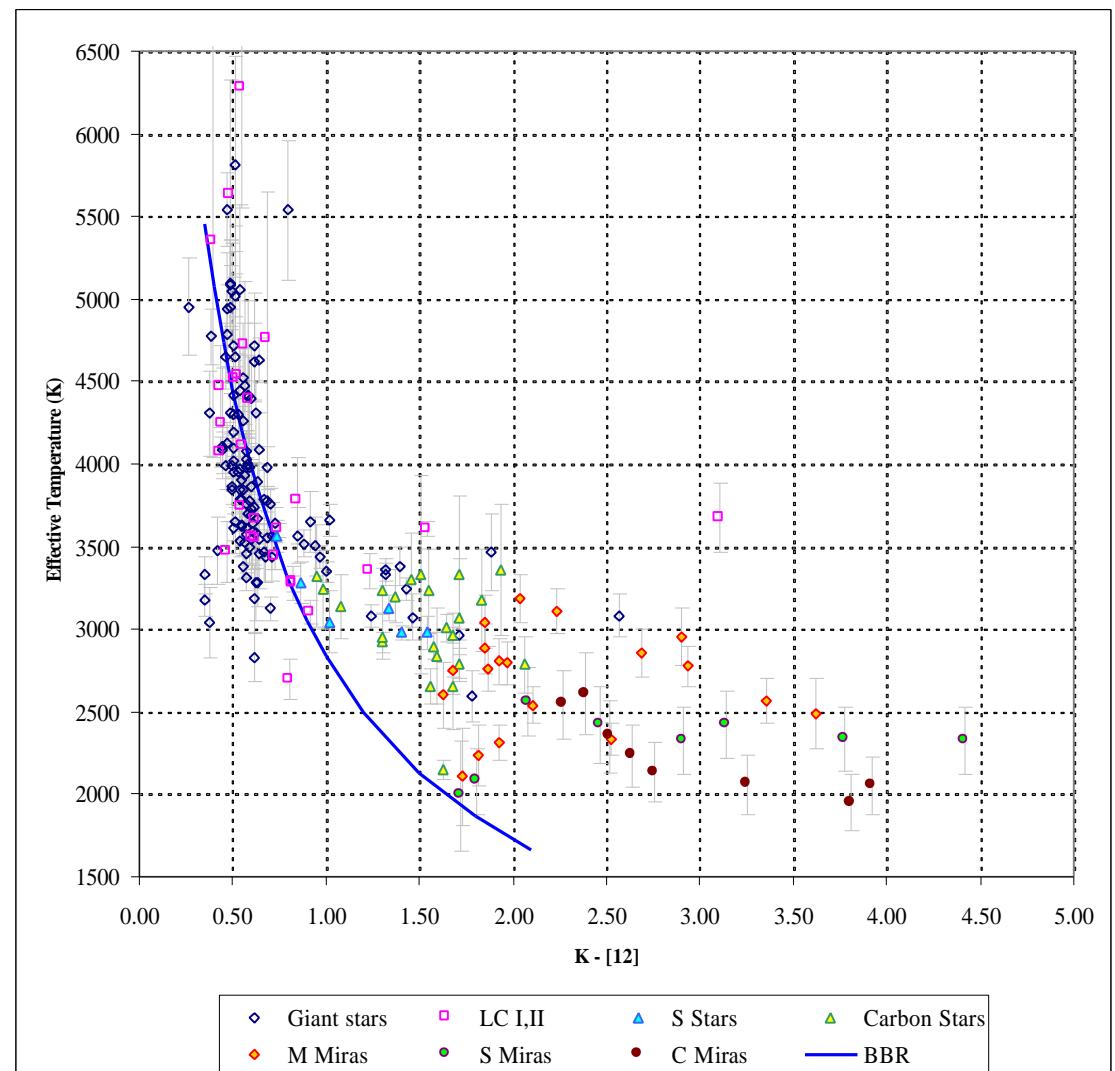
Effective Temperature vs. V-K Color

- Blue: Blackbody behavior
- Indications of increased absorption bands at V at low T_{EFF} (Barbuy *et al.* 1992, Jørgensen 1994)
- Clear separation of the abundance subtypes into regions on the plot



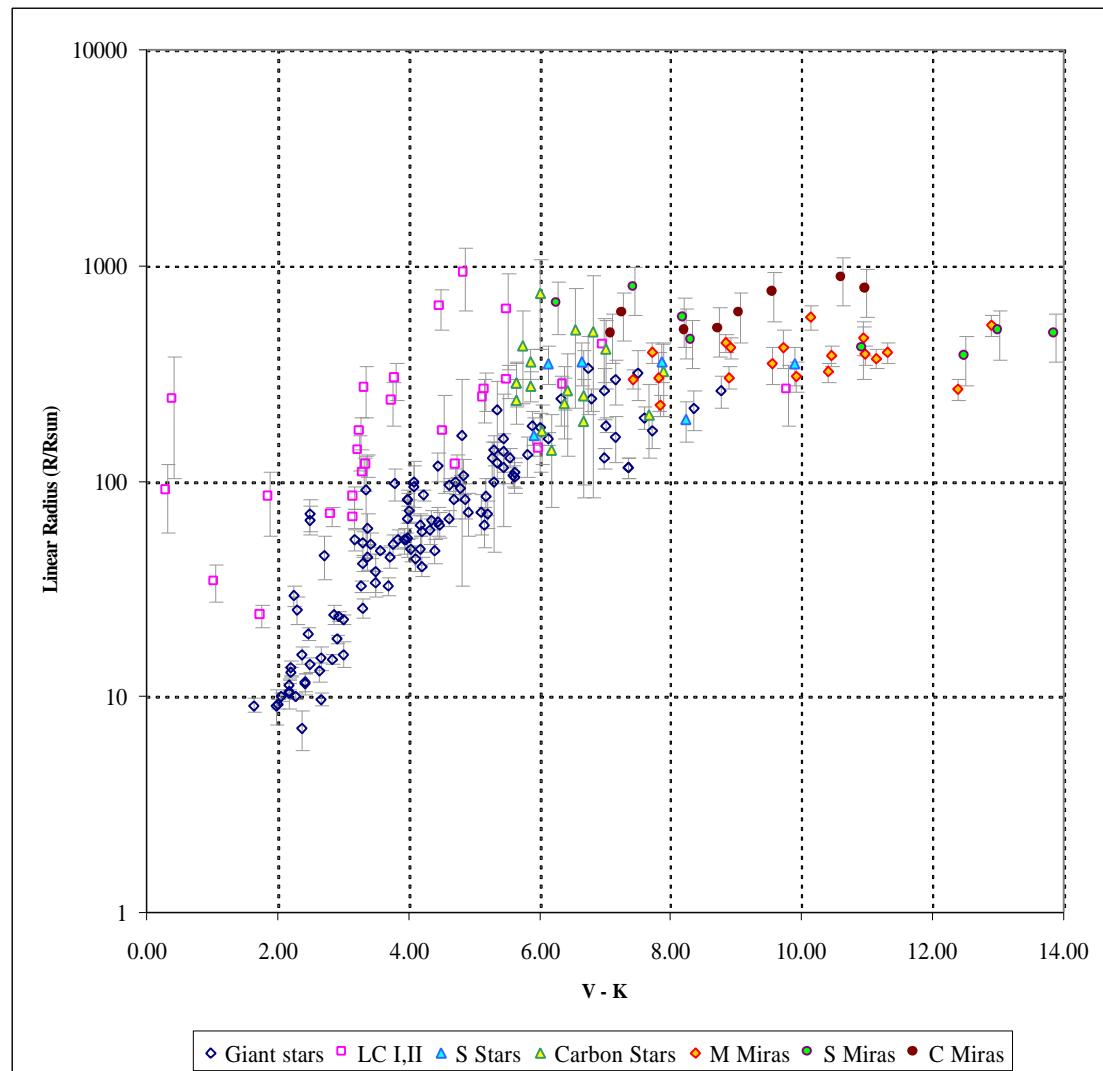
Effective Temperature vs. K-[12] Color

- K-[12] reasonable indicator of dusty mass loss
- Blue: Blackbody behavior
- Substantial departure from BBR curve at K-[12] ~ 0.80 by Miras, carbon stars
- Indication of onset of mass loss (Le Sidander & Le Bertre 1996, Beichman *et al.* 1990) for the more evolved stars



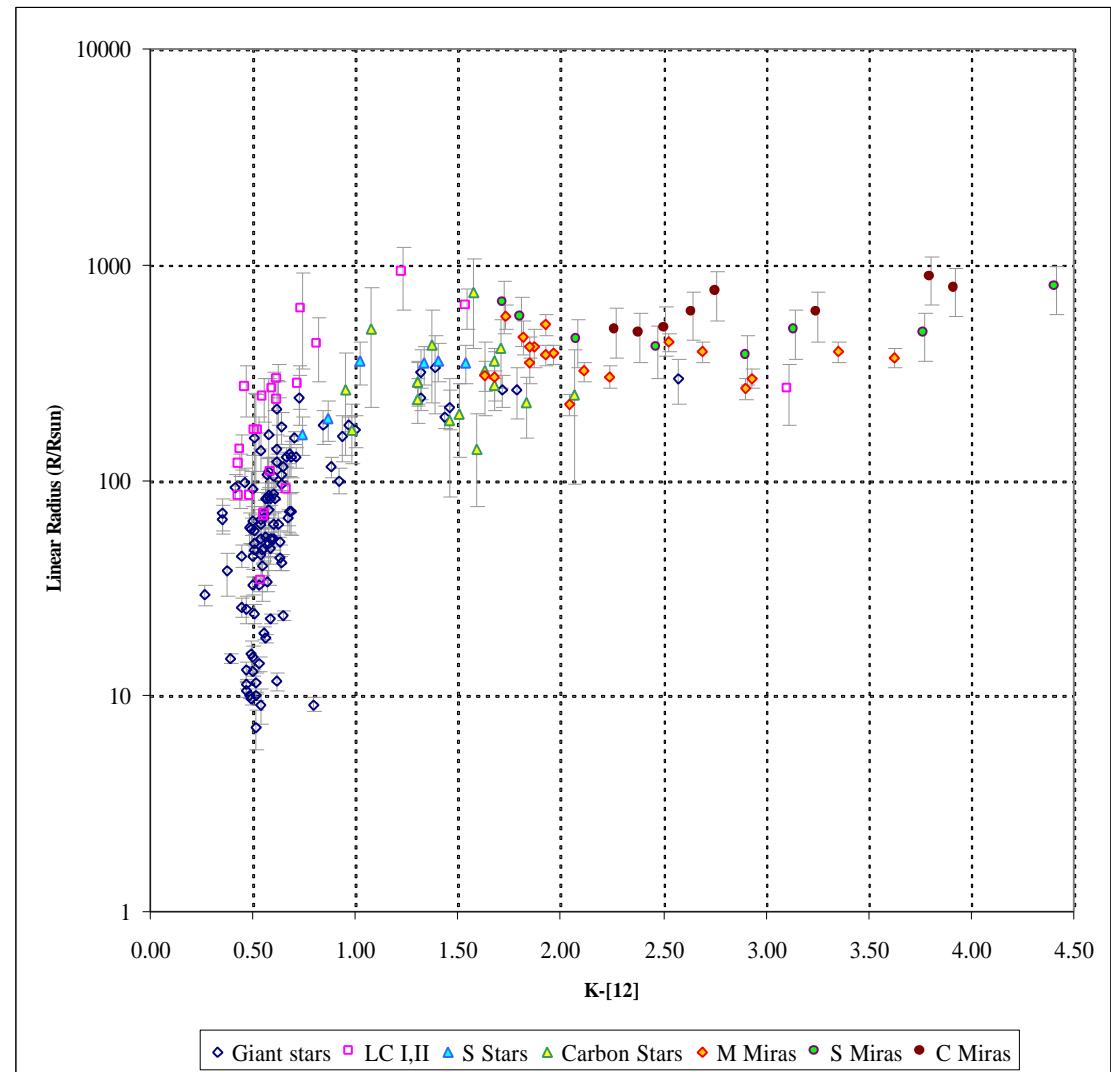
Radius vs. V-K Color

- Separation of luminosity class I,II versus III stars
 - Resolves some of the degeneracy of the radius/V-K relationship
- Giant stars fairly well behaved
- Well-defined lower edge curve
 - Change in power law at $V-K = 4$: $R \sim (V-K)^4 \rightarrow R \sim (V-K)^2$



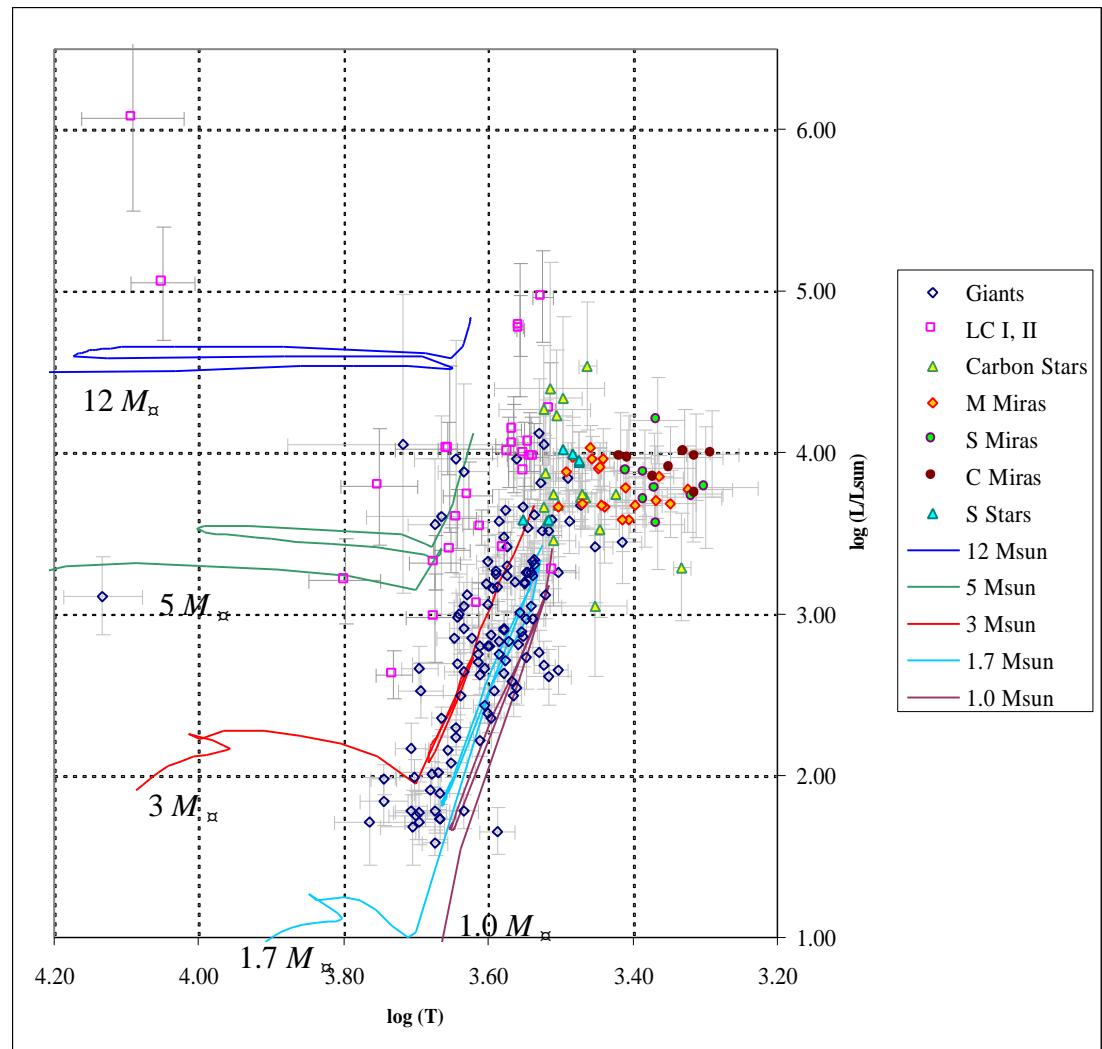
Radius vs. K-[12] Color

- Separation of luminosity class I,II versus III stars
 - As with V-K, clear tendency for supergiants/bright giants to be larger at a given color
- Dataset is consistent with progression of stars from oxygen rich → S-type → carbon, with stars growing in size as they redden



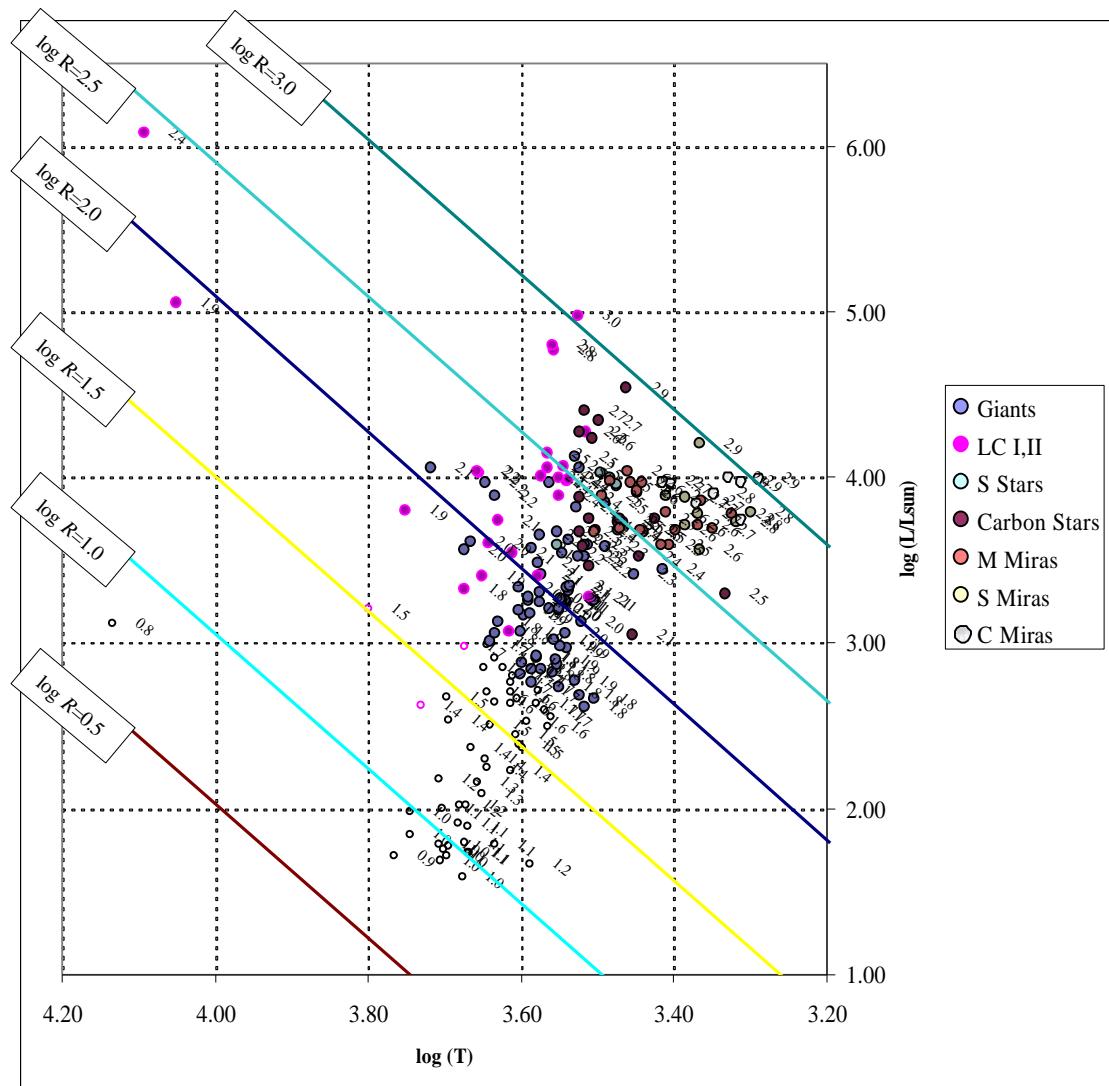
Luminosity vs. T_{EFF} with Model Tracks

- Model Tracks:
 - All tracks are Z=0.02 (solar)
 - Tracks from 1.0 - 12 solar masses (Schaller *et al.* 1992, Charbonnel *et al.* 1996)
- Good general agreement with the tracks
 - Underrepresentation of lower mass stars?
- Poor sampling of hotter stars
 - Selection effect



Luminosity vs. T_{EFF} by Radius

- Plot points scaled by radius
- Gradual gradient in radius from hot+dim to cool+bright
- Good comparison in measured values versus expected lines of constant radius (Iben 1991)



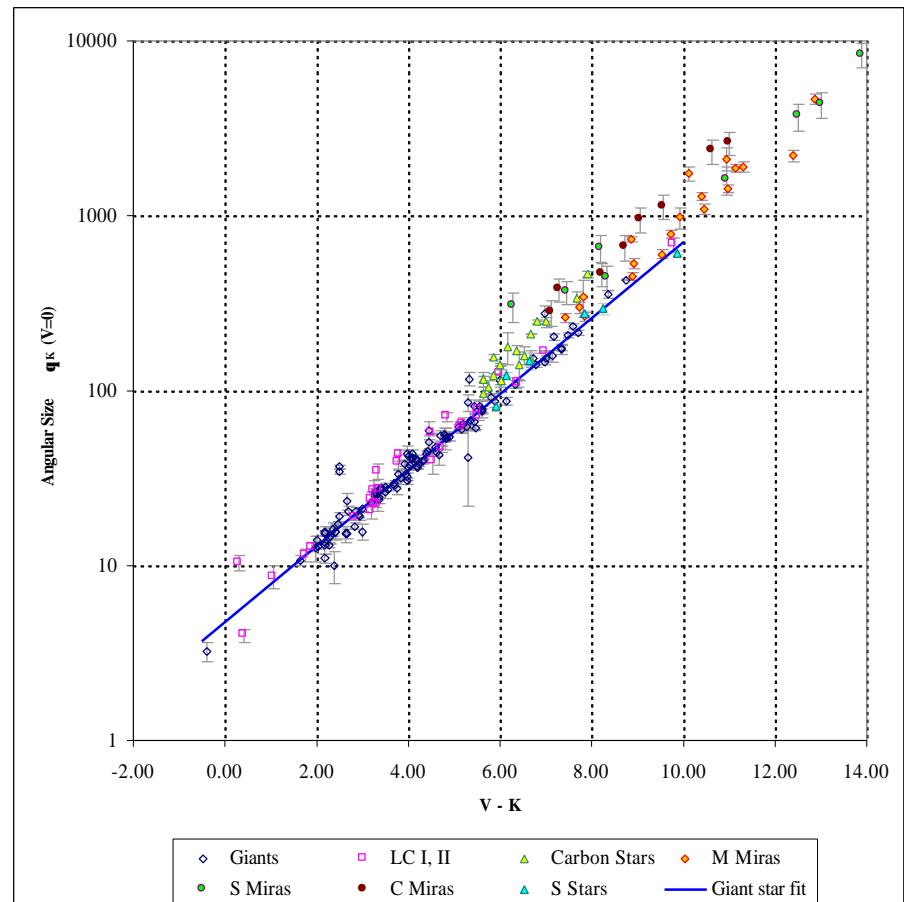
Apparent Angular Size vs. V-K

- Luminosity class III best fit line:

$$q_{K, V=0} = 10^{0.632+0.226 \times (V-K)}$$

(Angular size measured at K, scaled to apparent brightness of V=0)

 - Avg. deviation of values from fit of 9.6%
 - $\sigma^2 = 5.3$
- Good agreement with LC I, II
 - Avg. deviation of values from fit of 9.7%
- Noticable displacement of carbon stars, Miras from luminosity class I, II, III



Example Program: Halo Giants

Star	[Fe/H]	Angular Size θ_{UD} (mas)	Bolometric Flux (10^{-8} erg $\text{cm}^{-2} \text{s}^{-1}$)	Effective Temperature (K)	Hipparcos parallax (mas)	Radius (Rsun)
HDC122563	-2.71	0.921 +- 0.290	18.1 +- 4.5	5,031 +- 851	3.8 +- 0.7	26.1 +- 9.5
HDC165195	-2.2	0.913 +- 0.223	10.9 +- 4.2	4,449 +- 691	2.2 +- 1.0	44.6 +- 23.0
HDC232078	-1.5	0.741 +- 0.104	7.9 +- 3.5	4,564 +- 598	1.6 +- 1.1	49.8 +- 34.9

- Can use interferometry for investigation of stars of specific interest
 - Studies of metal-deficient stars could benefit from T_{EFF} measures
- Challenges for this particular investigation
 - Small apparent size of stars make measurements susceptible to calibration errors
 - Poorly established F_{BOL} - room for improvement?
 - Large errors in parallax - better estimators of distance available?

References

- Angular sizes:
 - Dyck *et al.* 1996a, 1996b, 1998
 - Hanbury Brown *et al.* 1974
 - Ridgway *et al.* 1980
 - van Belle *et al.* 1996, 1997, 1998
- Model evolutionary tracks:
 - Charbonnel *et al.* 1996
 - Iben *et al.* 1991
 - Schaller *et al.* 1992
- Photometry:
 - Gezari *et al.* (1996)
 - IRAS PSC (1986)
 - SIMBAD, VizieR, AFOEV, AAVSO
- All papers by Dyck *et al.*, van Belle *et al.* are online at:
<http://huey.jpl.nasa.gov/~gerard>